Particle Acceleration in SNRs, Clusters, and Elsewhere

What might future X-ray observations teach us?

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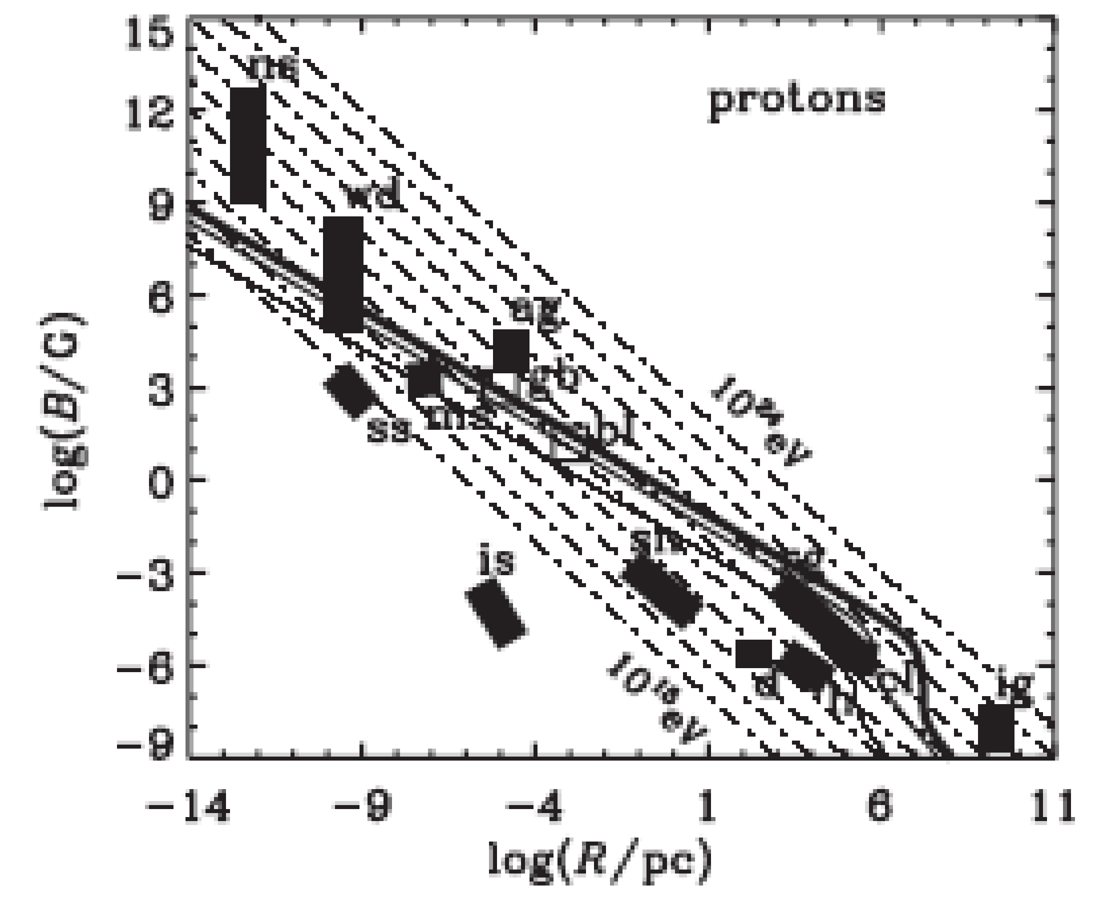
(with help from C. Sarazin, A. Decourchelle, K. Dyer, and others)

Particle Acceleration in Astrophysical Settings

- Nonthermal processes (acceleration) occur in numerous astrophysical settings from stellar flares to intracluster medium; operate in large range of time and length scales
- Accelerated particles have substantial energy content; affect dynamics of environment creating them
- Often acceleration is observable manifestation of the most extreme conditions in most extreme objects
- Fundamental connection to origin of cosmic rays (and UHE cosmic rays in particular)



Magnetic field stength vs gyroradius for various proton energies. Solid lines represent attainable energy from shocks -heavy line represents maximum efficiency shock (all energy used for acceleration). Blocks represent ranges for various astrophysical objects.
Torres & Anchordoqui (2004), after Hillas (1984)

Particle Acceleration Basics

- Two basic acceleration sites
  - Shock fronts - kinetic energy plus magnetic turbulence
  - Current sheets - magnetic energy
  - Both are observable in solar corona
  - [Solar corona is possibly the best place to study injection]
- We observe only by-products of interaction between accelerated particles and their environment
- Synchrotron radiation if B fields present
- IC if low energy photon field present
- Inferences about particle spectrum and acceleration mechanism requires (strong) connection with theory and observations in other bands (especially radio)
- Injection is not well understood in any environment

Key Themes

- Particle acceleration is fertile area of investigation for future X-ray missions
- Our knowledge of X-ray manifestations of acceleration is embryonic
- Configuring new missions to address acceleration offers challenges

Astrophysics Questions

- What can we learn about the process and products of particle acceleration?
- What is the energy content of the accelerated particles?
- What is the effect of the accelerated particles on the dynamics and evolution of the accelerating regions?

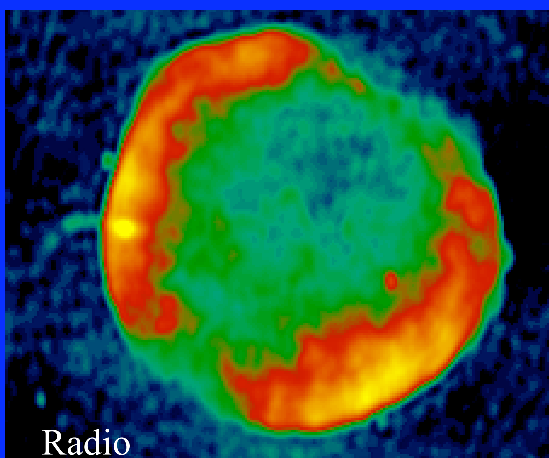
Observational Questions

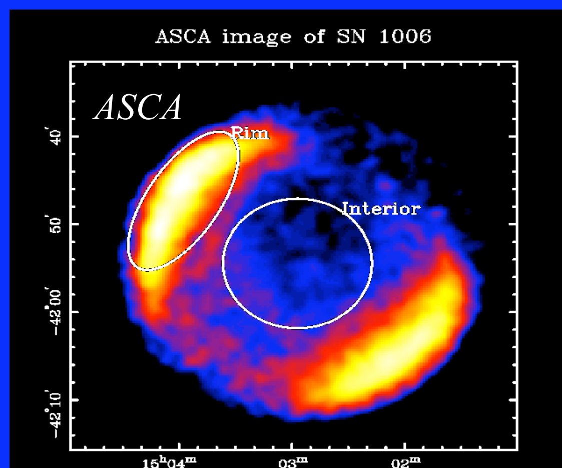
(specific to X-rays and derived from astrophysics questions)

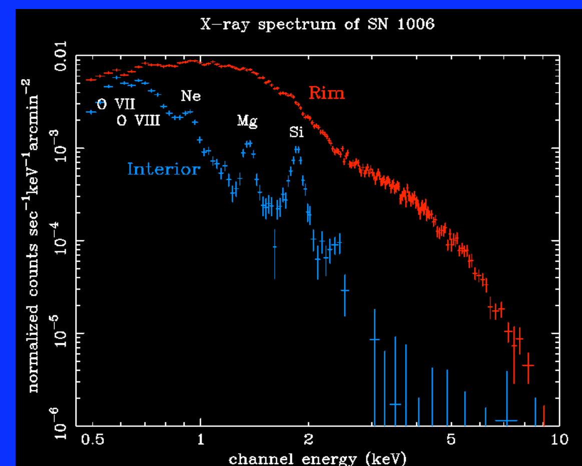
- What is the photon emission mechanism?
- What is the relationship between the X-ray emitting region and emission in other bands (radio, TeV)?
- What is the energy spectrum of the accelerated particles (including E_{max})?
- How does this spectrum evolve with source age?
- What are the conditions in the acceleration region?
  - Shock compression ratio
  - B field strength, morphology

Evidence for shock acceleration in SNRs

- SNRs - main source of cosmic rays with $E<3\times10^{15}$ eV?
  - Strong shocks - site for 1st order Fermi acceleration
  - Radio emission - presence of relativistic GeV electrons
  - X-ray observations of synchrotron emission => TeV electrons
- First evidence of TeV electrons found in SN1006
  - X-ray synchrotron emission in bright rims, and thermal emission throughout remnant; X-ray matches radio



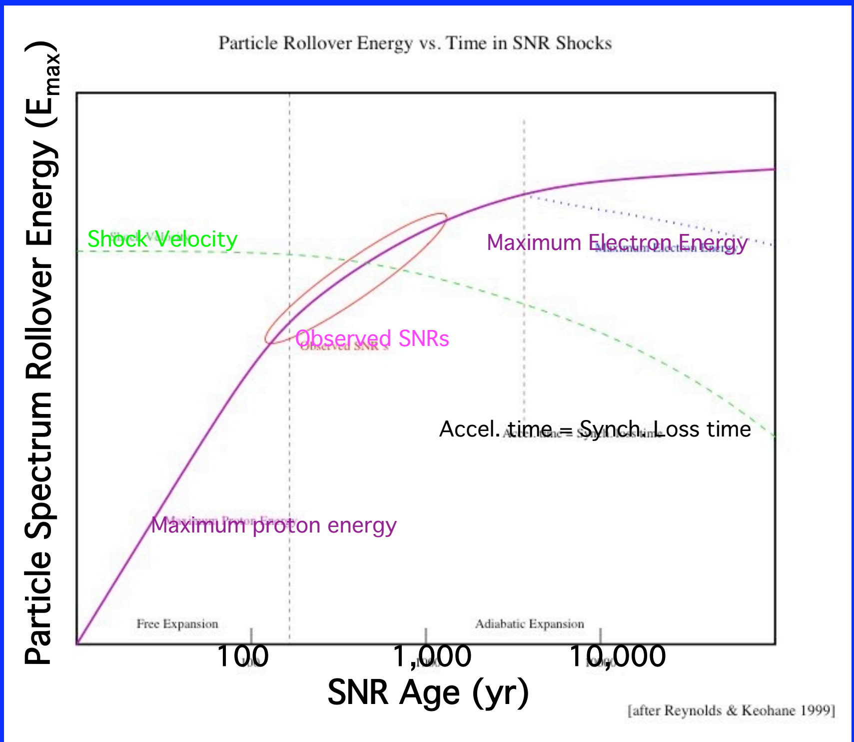




- Nonthermal spectral components now detected in two groups of SNRs
- - historical, ejecta dominated remnants
- - X-ray/radio dim SNRs

Energetics of shocked particles in SNRs

- Acceleration via 1st order Fermi process - proportional to u^2 and B
- Limits to maximum energy from three sources
  - Age ($t_{accel}>t_{SNR}$) $E_{max} \sim 8\times10^{-4}\, B\, u_8^{\,2}\, t$ ergs
  - Losses ($t_{accel}>t_{sync}$) $E_{max} \sim 0.1\, B^{-1/2}\, u_8$ ergs
  - Escape ($\lambda_e>\lambda_{max}$ of MHD turbulence($<R_{SNR}$)) $E_{max}\sim e\, B\, \lambda_{max}$ ergs
- All existing measurements require slope change between radio and X-ray (which can be described at the basic level by simple loss models)



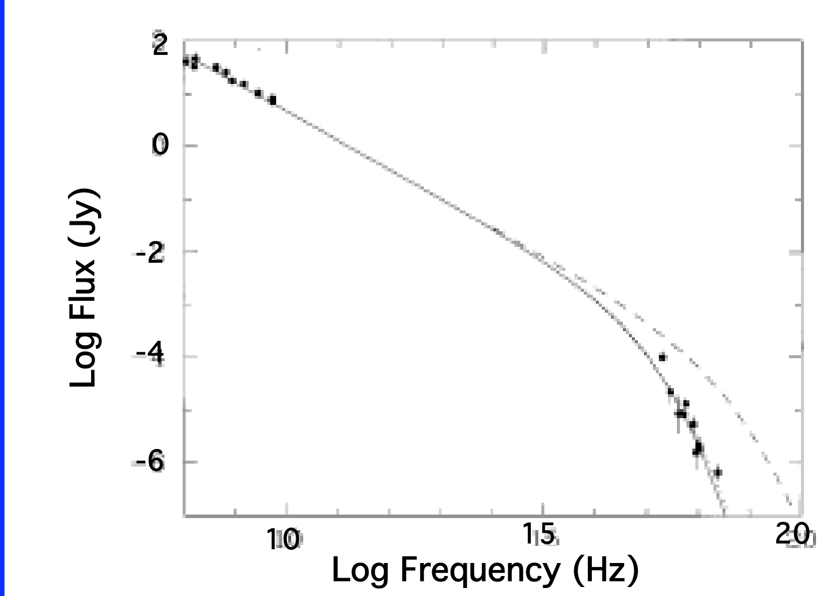
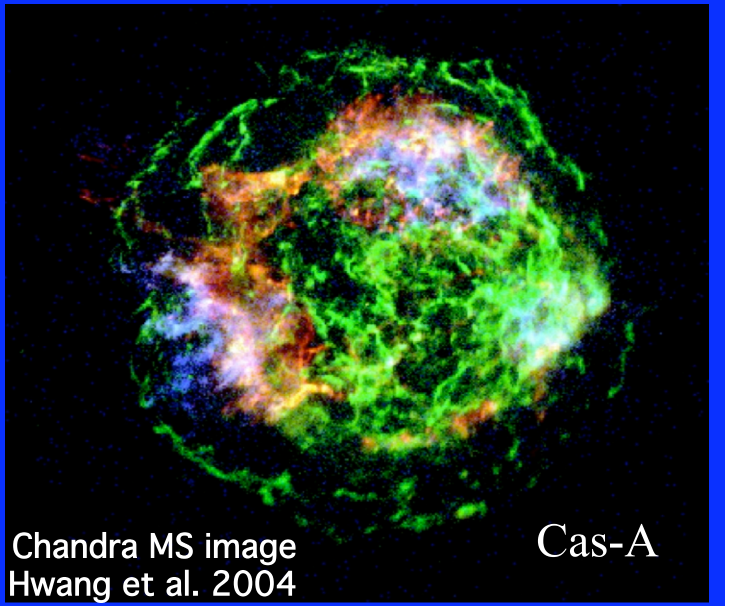
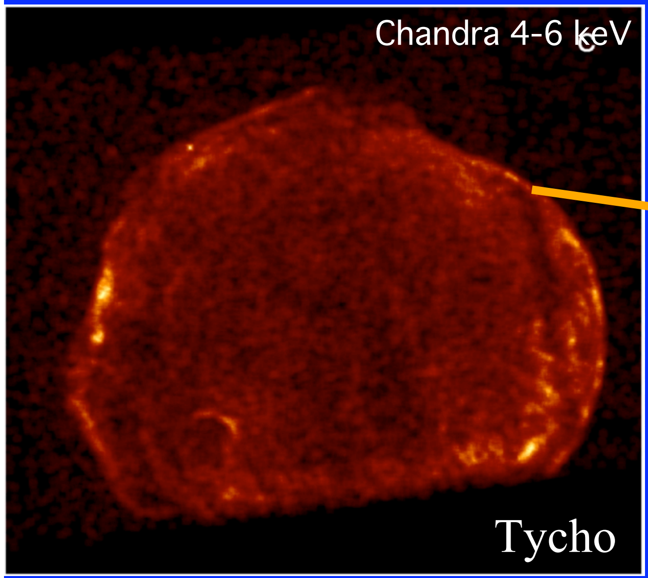


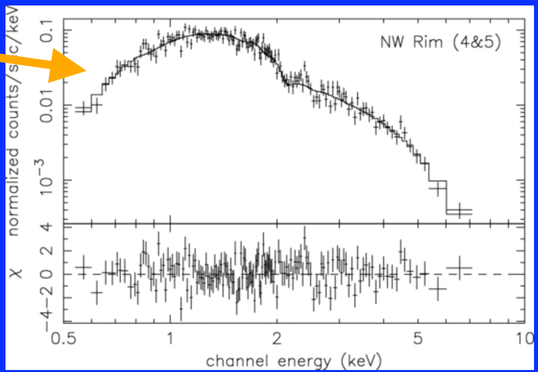
FIG. 1.—Model spectra from radio to X-ray frequencies. Radio data are collected in Ford & Reynolds (1995), and X-ray data are collected in Hamilton et al. (1986). The solid line shows the model with escape ($\lambda_{max} = 10^{17}$ cm) and with $B_1 = 3\ \mu$G and $f = 10$. The dashed line has the same B_1 and f, but no escape. The dotted line invokes no escape, and has $B_1 = 0.6\ \mu$G and $f = 1$.

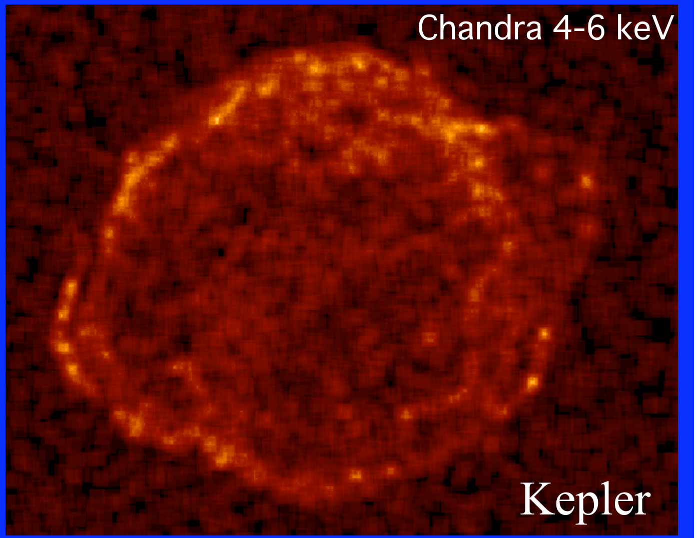
Historical, Ejecta-dominated SNRS

- Remnants are dominated by thermal emission from ejecta
- All show narrow rims of hard emission with (nearly) featureless spectra
- Hard X-ray/radio correlation at rim with varying fidelity
- Other interpretations of hard emission - e.g., nonthermal Bremsstrahlung (esp. for Cas A)
    - Establish by observing high energy spectrum



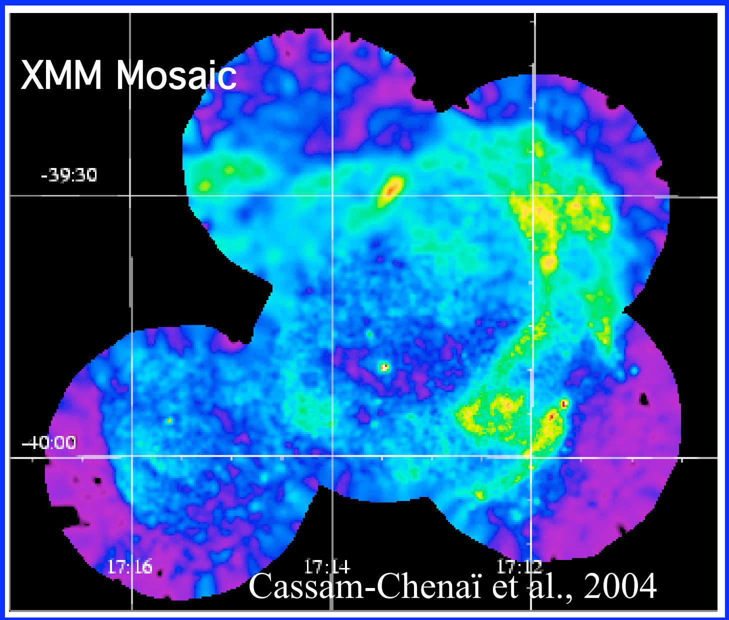




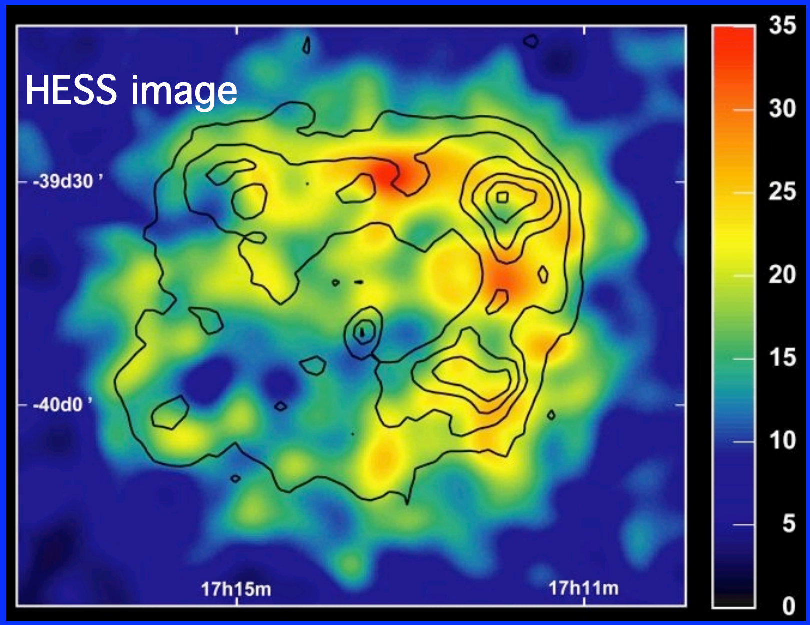


Synchrotron dominated SNRs

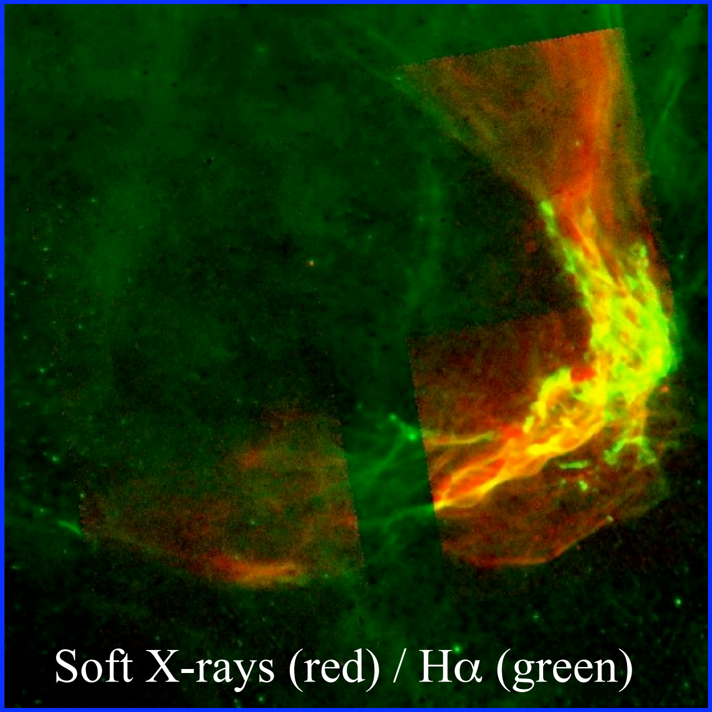
- Three such remnants known: RX J1713.7-3946,
  RX J0852.0-4622. SN1006 (intermediate case)
- Strong X-ray/radio correlation
- Remnants expanding in low density medium
- High shock velocity with less deceleration
- No material to sweep up - no foreground thermal emission
- Result is low surface brightness in all bands - hard to find!
- Best environment to study shock acceleration
- RX J1713-3946 - best studied example
  - Pure nonthermal spectrum observed; $N_H \propto SB$
  - HESS, Cangaroo spectum, image suggest TeV γ-rays from hadrons

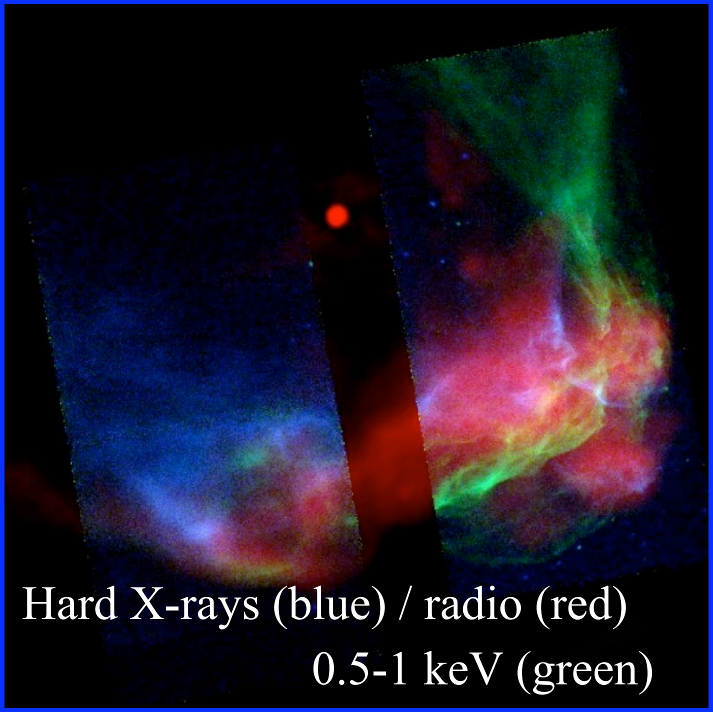


Cassam-Chenaï et al., 2004



One exception - RCW 86
Acceleration in reverse shock?





Rho et al. 2002

- Hard emission arises in ejecta region, behind shock front; near forward shock interaction with dense ISM
- Acceleration at reverse shock difficult to see in other SNRs
  - Emission dominated by thermal emission
  - Reverse shock sometimes close to forward shock

Maximum Inferred Electron Energies

- All SNRs with hard tails require a spectral break between radio and X-ray.
- Modeling with single component spectrum with losses producing turnover yields estmate of E_{max}.
- E_{max} estimates typically 10-100 TeV - but these are for electrons.
- Electron E_{max} consistent with turnover in electron CR spectrum.
- Expect decoupling between electrons and protons.
- Must rely on other means to infer E_{max} for protons

TABLE 2

ROLLOFF FREQUENCY AND MAXIMUM ELECTRON ENERGY UPPER LIMITS

Object	$\nu_{rolloff}$ (10^{16} Hz)	$\nu_{rolloff}$ (keV)	$E_{max}[(B/10\mu G)]^{1/2}$ (ergs)	$E_{max}[(B/10\mu G)]^{1/2}$ (TeV)
Kes 73[a]	150	6	290	200
Cas A	32	1	130	80
Kepler	11	0.5	79	50
Tycho	8.8	0.4	70	40
G352.7−0.1	6.6	0.3	60	40
SN 1006[b]	6	0.2	57	40
3C 397	3.4	0.1	43	30
W49 B	2.4	0.1	36	20
G349.7+0.2	1.8	0.07	31	20
3C 396	1.6	0.07	30	20
G346.6−0.2	1.5	0.06	29	20
3C 391	1.4	0.06	28	20
SN 386[a]	1.2	0.05	26	20
RCW 103[a]	1.2	0.05	26	20

NOTE.—Values shown in this table are upper limits, because in each case the bulk of the continuum is assumed to be synchrotron. Values shown in cgs units were rounded to two digits, while their common-unit equivalents were rounded to the more reasonable one significant figure. Note that while 10 μG was assumed for a standard SNR magnetic field, Cas A's magnetic field is about 1 mG (i.e., $E_{max} \sim 8$ TeV), and others are quite uncertain.

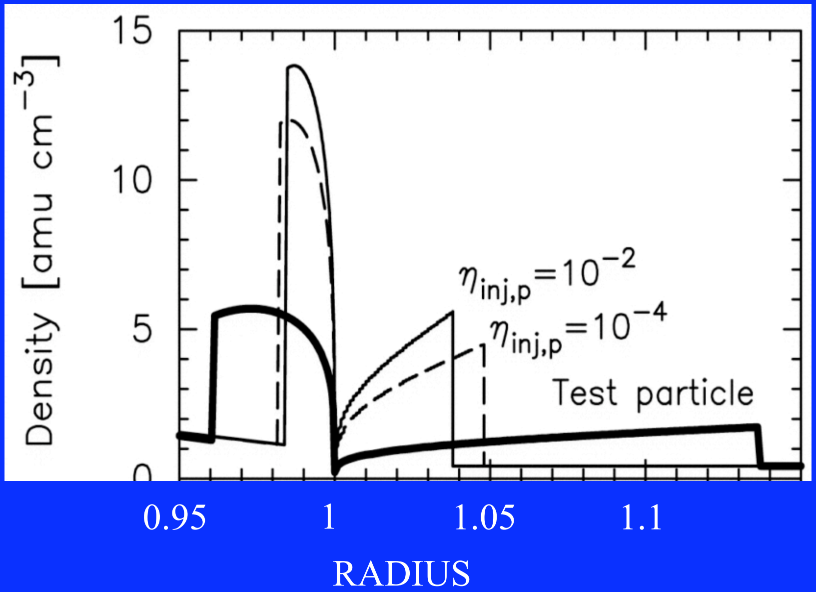
[a] Contains a known hard X-ray central source.

[b] This value of $\nu_{rolloff}$ is not a limit but results from the model of the nonthermal X-ray emission by Reynolds (1996). See § 4.

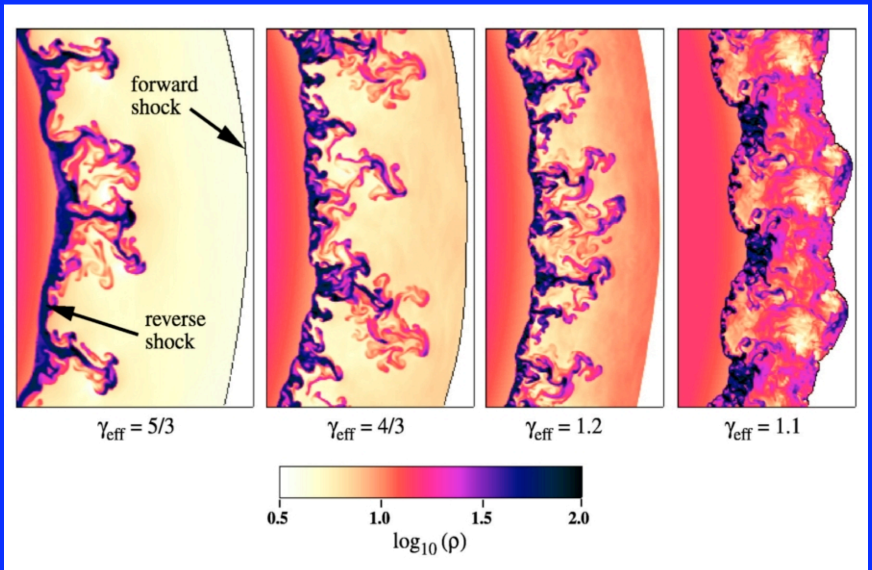
Reynolds & Keohane 1999

Indirect evidence for cosmic ray acceleration

- In a few remnants (E0102-72, Tycho) electron temperatures inferred from expansion rate and X-ray spectroscopy are highly discrepant (Hughes et al 2002; Hwang et al. 2002)
- Can be explained by shock modification due to losses as a result of efficient particle acceleration
- Conversion of a few percent shock energy into accelerated particles can have major effect on shock structure and dynamics
- Support from measured widths of interaction regions in Tycho, Kepler



Decourchelle et al. 2000; Ellison et al. 2004



Blondin & Ellison 2001

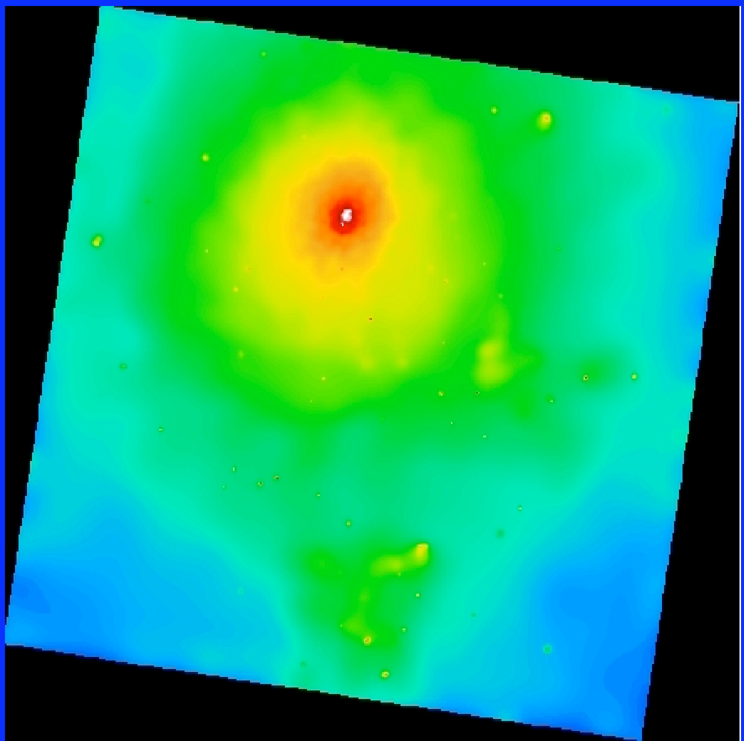
Questions about shock acceleration in SNRs

- How efficient is cosmic ray acceleration in SNRs?
- What is the maximum energy of the accelerated particles?
- How large is the magnetic field? Is it turbulent?
- Is the magnetic field amplified at the shock front(s)?
- Is there evidence for ion acceleration in SNRs?
- How well does X-ray nonthermal emission correlate with radio - is a single particle population responsible for both?
- What is the effect of particle acceleration on SNR dynamics?

Progress depends on ability to detect and perform spatially resolved broad band spectroscopy of shock structures in nearby SNR

Cluster Mergers as Energy Sources

- Clusters form hierarchically
- Major cluster mergers are most energetic events in Universe since Big Bang
- Major cluster mergers, two subclusters, $\sim 10^{15}$ M_{sun} collide at ~ 2000 km/s
- Shocks are the main heating mechanism of intracluster gas
- E (merger) ~ 2 x 10^{64} ergs
- E (shocks in gas) ~ 3 x 10^{63} ergs



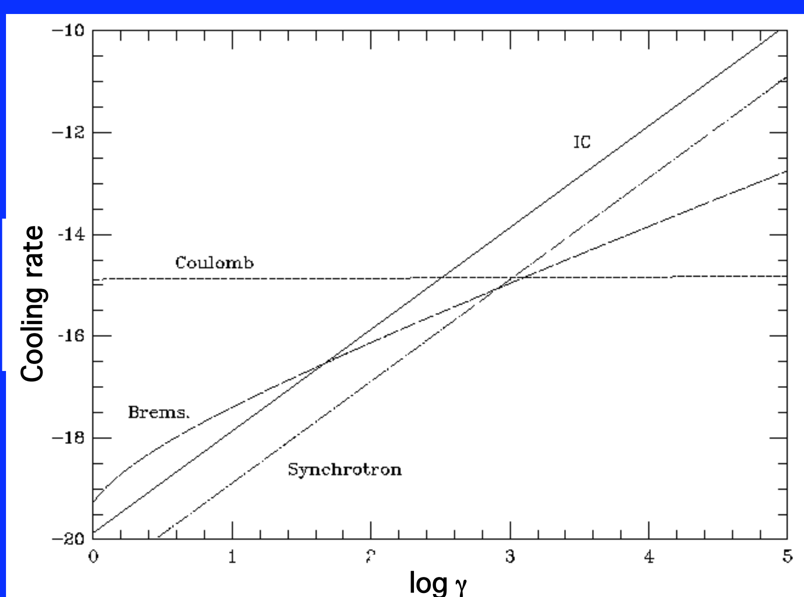
Merger in A85 (Chandra image - Kempner et al. 2002)

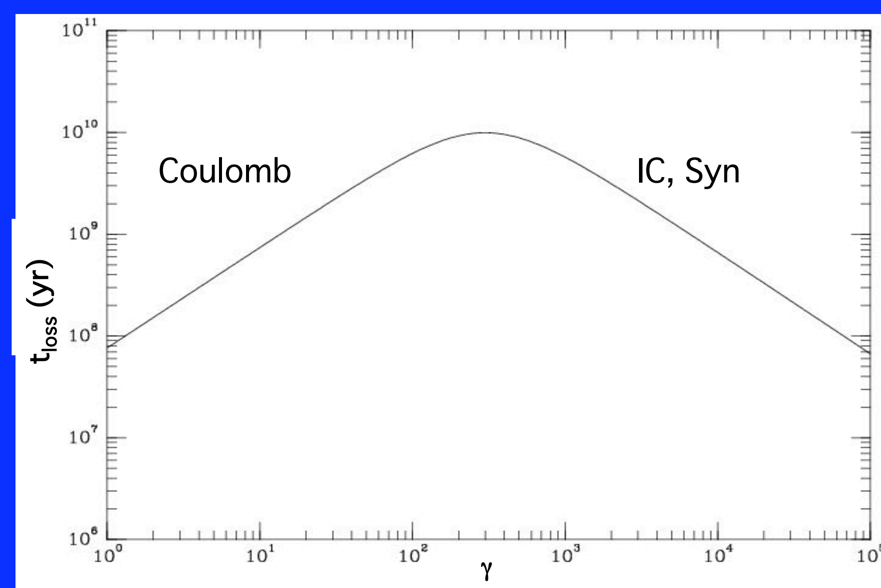
- Significant distortion of subcluster
- Merger is shaping cluster radio sources

Clusters: Bags full of Cosmic Rays?

- Total energy in each merger shock is $\sim 3 \times 10^{63}$ ergs
- By analogy with SNR, if a few percent of shock energy is converted to high energy particles, then:

  $E_{CR,e} \geq 10^{62}$ ergs; $E_{CR,ion} \geq E_{CR,e}$
- Coulomb losses to thermal plasma at low energies (γ<300, E<150 MeV)
- IC, Synchrotron at high energies
- Strong gravity, ICM, B hold CRs
- Large → long diffusion times $\gg 10^{10}$ yr
- Low gas, radiation densities → losses low

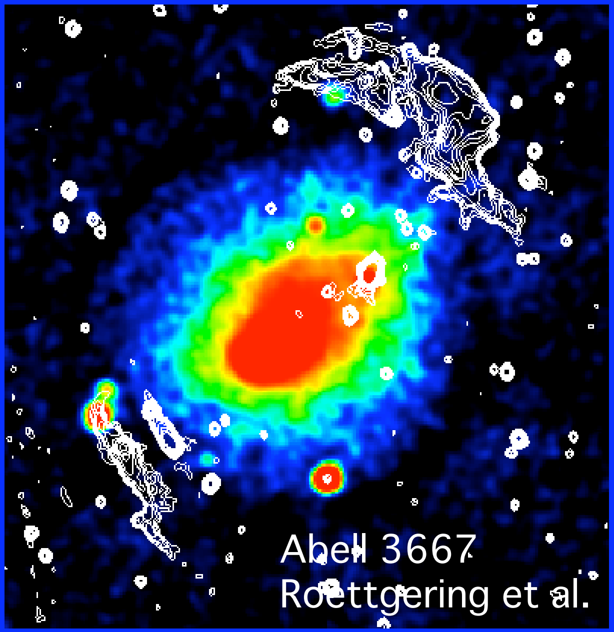




Takizawa 2002, Sarazin 2004

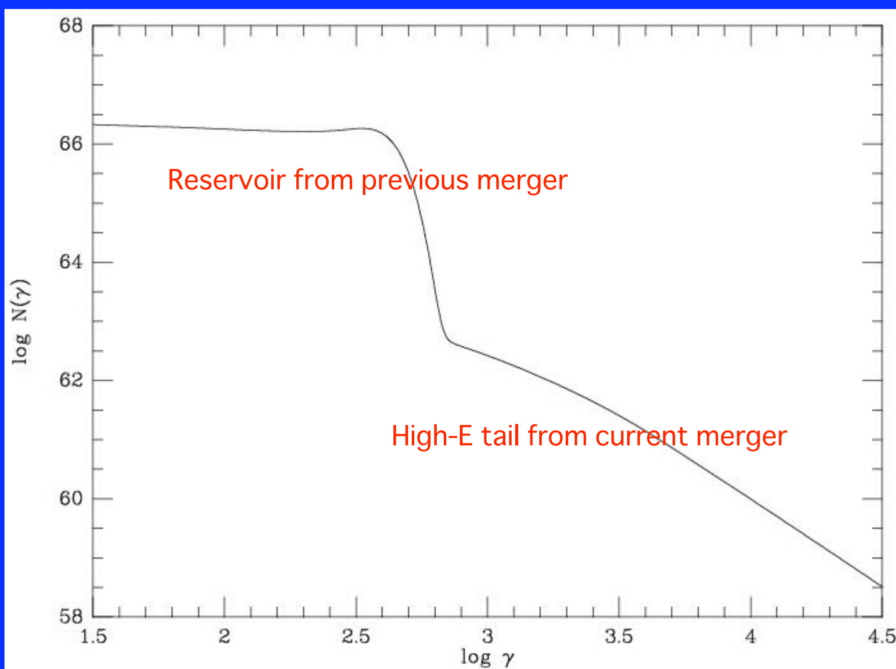
Radio Emission from Clusters - Halos and Relics

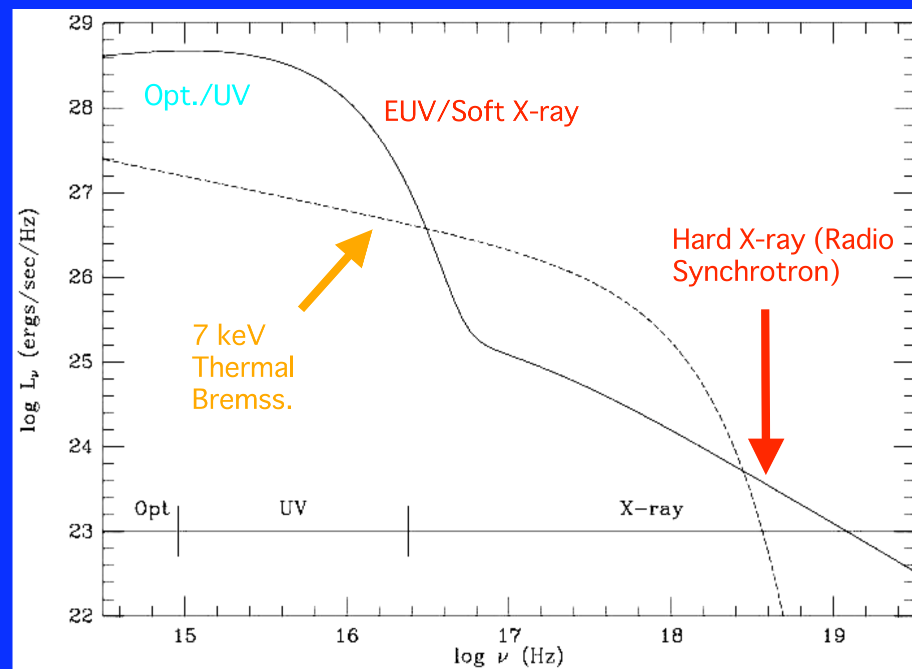
- Presence of radio emission attests to presence of GeV particles in clusters
- Two morphologies
  - Haloes
    - turbulent acceleration?
  - Relics (everything that is not a halo)
    - shock acceleration?



Typical CR e⁻ Distribution & Resulting IC Spectrum

- Lots of low energy e’s (γ ~ 300, E ~ 150 MeV) from previous acceleration
- Tail of high E electrons from current merger acceleration (and small number of secondary electrons)
- Hard X-ray Tail (Radio Synchrotron from similar electrons); only in clusters with current merger
- EUV/Soft X-rays from IC scattering of CMB photons prime mechanism
- Nonthermal bremsstrahlung (NTB) from low energy tail is another plausible source
- Hard X-ray observations can discriminate by spectral shape
- IC and NTB are both inefficient radiation processes



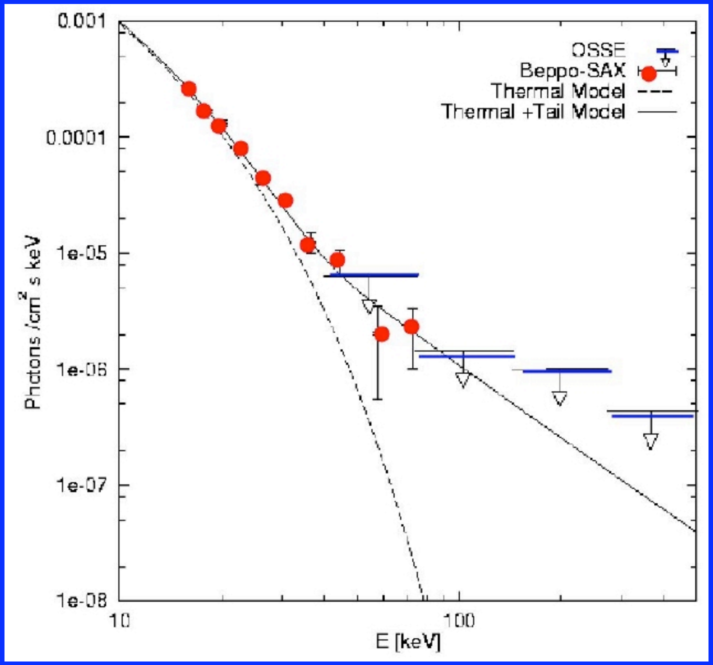


Inverse Compton or Nonthermal Bremsstrahlung?

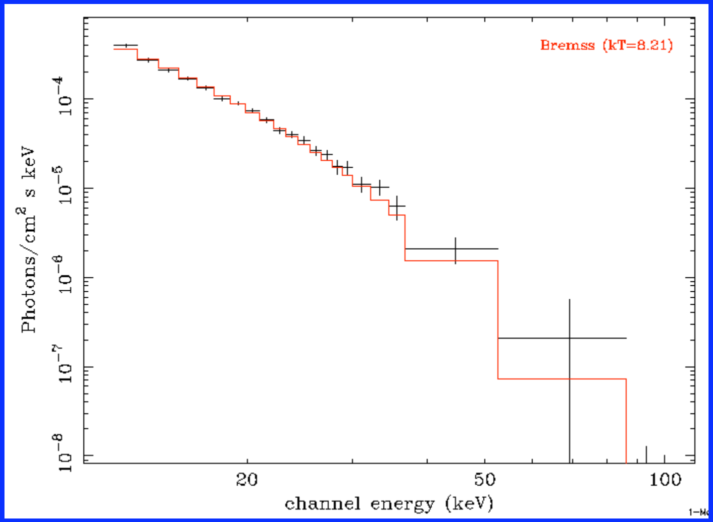
- Very low inferred magnetic fields are a problem for IC interpretation.
- Nonthermal Bremsstrahlung (NTB) arises from low energy tail of electrons being accelerated or remnant of older nonthermal population losing energy
- NTB models produce 20-100 keV power law spectra
- IC dominates NTB for flat spectra (strong shocks) or electron spectra without cutoff at ~1 GeV. Those without cutoff underpredict EUV.
- NTB is therefore possible source of hard X-rays in clusters showing no radio emission.
- Both are inefficient radiation processes, requiring several percent of number of electrons in thermal ICM and substantial nonthermal energy (>10 percent even for IC).
- Observations thus far are unenlightening; and in fact support either mechanism.
- Refs - Sarazin & Kempner (2000), Takizawa (2002)

Observational Evidence(?) for Acceleration in Clusters

- Possible detections of hard X-ray excesses from clusters with BeppoSAX & RXTE (e.g., Coma, A2319, A2256)
    - Difficult to detect in non-imaging detectors above background and dominant thermal emission
    - Detections weak ~ 4 σ
    - Spectral shape not constrained
- In A2199, inferred B<0.2 μG if IC; much less than the nominal 1 μG; Kempner & Sarazin (2000) conclude emission is nonthermal Bremsstrahlung
- Results are controversial:
    - Deep BeppoSAX Coma observation:
    - excess not detected by Rossetti & Molendi (2004); confirmed by Fusco-Femiano et al. (2004)



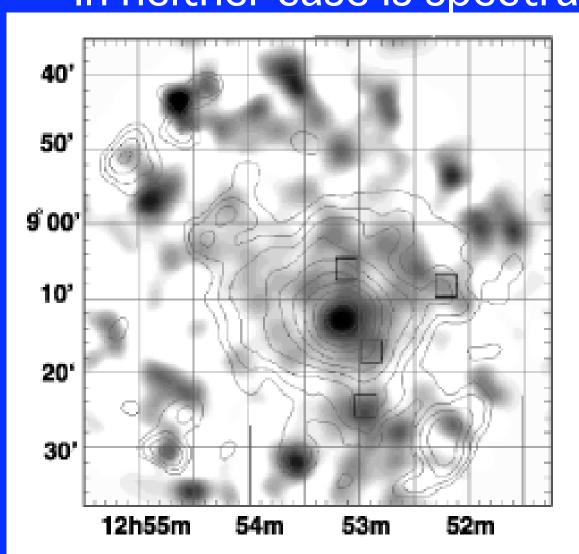
Coma HXR BeppoSAX (Fusco-Femiano et al.)



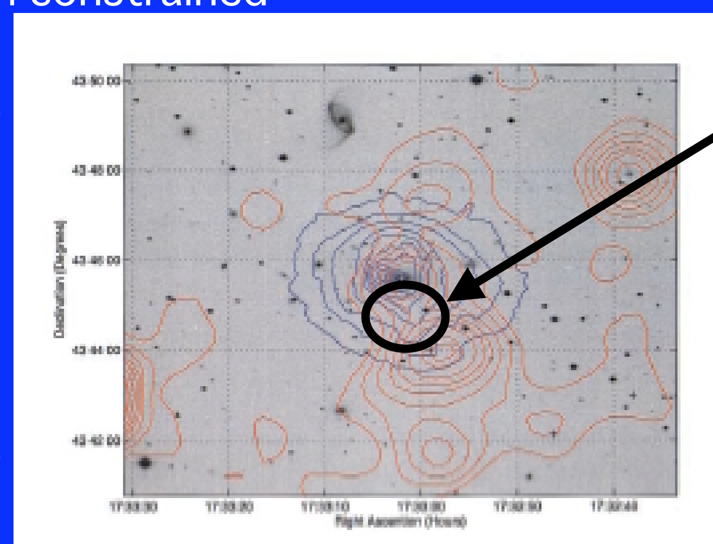
Nonthermal Hard X-ray Emission from Poor Clusters and Groups?

- Difficult to see hard X-ray excess against luminous cluster X-ray thermal emission
- Look at poor clusters (with lower kT) or groups (with even lower kT); concentrate on those with radio halos
- Hard flux has been detected, but results are ambiguous
  - Fukawaza et al. (2001) detect extended hard halo in HCG 62 (20% of total)
  - Hudson et al. (2003a,b) detect hard emission in IC 1262, concentrated near (but not at) radio peak (~50% of 1.5-10.5 keV L_x)
  - In neither case is spectral form constrained

50’



8’



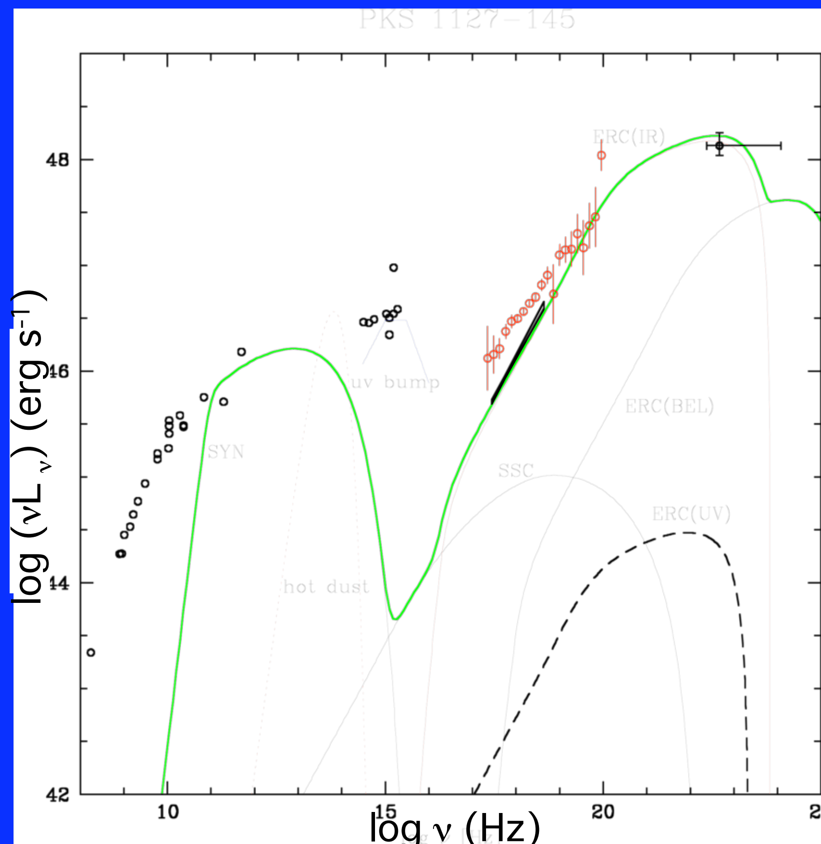
Approx. location of hard emission centroid (red is radio, black is total X-ray)

Questions about particle acceleration in Clusters

- How ubiquitous are nonthermal X-rays due to particle acceleration?
- Is the primary radiation source primary or secondary electrons?
- How well does X-ray nonthermal emission correlate with radio - is a single particle population responsible for both?
  - Do cluster radio relics and radio halos have different signatures associated with acceleration process?
- What is the total energy content of relativistic particles?
- What is the effect of particle acceleration on the dynamics of clusters?
- How does nonthermal emission in clusters evolve with redshift, and what does this tell us about the evolution of the dynamics of shocks in cluster mergers?
- What is the maximum particle energy?
- What is the magnetic field strength? Is it turbulent? Is it amplified?

Acceleration in AGN (blazars)

- Evidence of particle acceleration in jets from radio emission
- Broad-band spectra consist of two broad components: one in radio/IR/optical presumably radiating via synchrotron (polarization!) and the other in hard X-rays / γ -rays, presumably radiating via inverse Compton: both due to the same particle population
- The popular jet transport models can be classified as
  - * matter-dominated (proton, electron, positron) or
  - * electromagnetically dominated (Poynting flux, $B^2/8\pi$)
- Not possible to measure full particle content of jet in radio due to synchrotron self absorption at long wavelengths (where bulk of particles radiate)
- X-ray + radio (+ γ-ray) allows for full description of particle spectrum and measurement of B-field



Broad-band spectrum of blazar PKS 1127-145

Other sites of particle acceleration

- Massive star forming regions
  - Shocks in stellar winds and wind collisions accelerate particles
  - Acceleration efficiency, energy partitioning between ions and electrons unknown
- Accreting compact objects
- Jets from compact Galactic sources
  - Radio emission from Galactic microquasars
  - Evidence for particle acceleration at SS 433 jet termini in W50
    - Power law spectrum of hard X-rays (Safi-Harb et al.)
    - Jet kinetic energy converted to accelerated particles via collisions
- Stellar flares
  - Are solar processes reliable analogs of more active stars?
- Pulsar Wind Nebulae
  - Acceleration region within pulsar magnetosphere
  - We can study cooling of particles, transfer of energy to medium
- Gamma ray bursts

- High energy Cosmic Rays have to come from somewhere, and observations have called into question SNRs as the prime candidate

Looking ahead

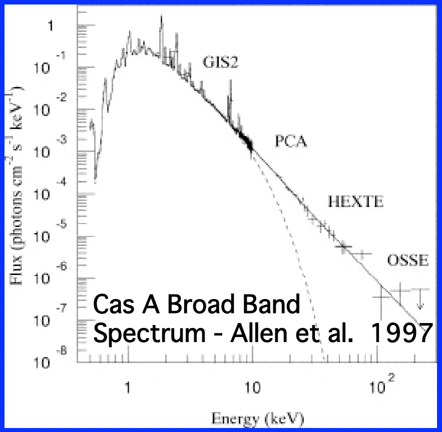
- Investigation of acceleration sites requires a combination of broad bandpass, modest-high angular resolution, good spectral resolution, and sensitivity to low surface brightness above ~5 keV.
- Primary need is sensitivity in 10-50 keV range, above thermal peaks
- Incremental progress will be made by current and planned missions
- Chandra
  - may isolate additional acceleration sites
  - lacks bandpass for definitive spectral measurements
  - High background severely limits imaging above ~5 keV
- XMM
  - Broader bandpass, higher throughput allows deeper view of high energy tails
  - Angular resolution limits detailed investigation of shock features
  - High background severely limits imaging above ~5 keV
- Astro-E2
  - HXD will measure spectrum of bright tails over broad bandpass
  - Cannot locate sites in extended sources
  - HXD should characterize hard tails in a few clusters, but no imaging
- NeXT/NuSTAR
  - Potentially major breakthroughs, especially for unresolved sources
  - Broad bandpass, moderate spectral resolution
  - Angular resolution and field of view may restrict cluster and SNR studies

Observational Questions
(specific to X-rays and derived from astrophysics questions)

- What is the photon emission mechanism?
- What is the relationship between the X-ray emitting region and emission in other bands (radio, TeV)?
- What is the energy spectrum of the accelerated particles (including E_{max})?
- How does this spectrum evolve with source age?
- What are the conditions in the acceleration region?
  - Shock compression ratio
  - B field strength, morphology

Observational capabilities needed/desired

- Bandpass 1-60 keV
  - Observe nonthermal above thermal band
- Field of view - ~$10'$ at all energies
  - Objects are large; need to see background
- Angular resolution - <$15''$ at all energies
  - Morphology studies impossible otherwise
  - Need <$5''$ to study SNR shocks
- Low background for SB studies
  - 2×10^{-4} cts s-1 cm^{-2} keV^{-1} (InFOCμS) => 750(fl/10 m) cts $arcmin^{-2}$ in 100 ks (worsens with longer f.l.)
- Effective area: Current HXT provides 10+ keV sensitivity in 100 ks to a surface brightness of 2×10^{-13} erg $arcmin^{-2}$ cm^{-2} s^{-1}
  - Arc minute spectroscopy of tail in cluster with 10 percent of $L_X \sim 10^{45}$ erg s^{-1} at z=0.05 with nominal HXT area
  - Would prefer larger effective area!
- Spectral resolution - modest above 10 keV
  - Spectrum is continuum; shape arises from origin
- Polarization sensitivity!
  - Emission mechanism; orientation of B field

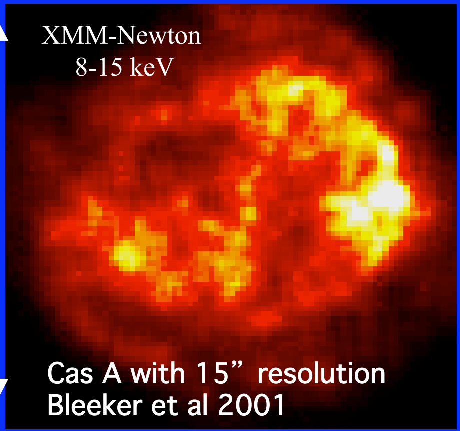


Cas A Broad Band Spectrum - Allen et al. 1997

30’


SN1006 Chandra mosaic

5’



Cas A with 15” resolution
Bleeker et al 2001